# Fast switching, High Accuracy LCoS for 3D Holographic Applications

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## ABSTRACT

*A 0.7-inch, 4K2K LCoS-SLM with full 2π radians phase modulation to cover depth-focus image was developed. The full phase modulation was found 0.9 and 1.5 ms under the digital driving scheme with $\Delta V = 1.75$ V at T=45 °C. A 200 mm depth of 3D reconstruction holographic image was demonstrated.*

## 1. INTRODUCTION

Microdisplays have developed to a key component of display and optics area in the recent years. In 2018, Google and LG presented a 120 Hz, 1443 ppi OLED display with 18M pixels in 4.3-inch for Virtual Reality (VR) head mounted displays (HMDs) which opened a new era for VR application [1]. In the same year, both JDI (SLC-IPS) and Sharp (IP-SFR) utilized a high pixel density (~1000 ppi) LCD panels for VR HMDs [2, 3]. Phase-only spatial light modulator (SLM) performs as 3D holographic display for near-eye AR glasses, automotive HUDs, holotable/box, and focal surface display for VR HMDs [4-7]. As a result, the demands of the ultra-high pixel density (> 4000 ppi) and light-weighted system of VR and AR application has been growing rapidly.

The ideal SLM requires full 2π radians phase to show depth-focus image. Not only that, the smaller pixel pitch (< 4 μm) and higher aperture are both needed to achieve the high diffraction angle and to enlarge the field of view (FoV). The binary phase modulation can be used found in DMD, MTN, FLCoS, π-shift ECB, or VAN LCoS phase modulation system. However, these devices suffered the significant quantization noise and low reconstructed image quality [8-10]. Samsung and ETRI have co-developed the glass-type SLM (SLMoG) with high resolution panel (pixel pitch from 3.0~3.76 um) [11, 12]. Unfortunately, the transmissive LC-SLM is problematic to accomplish a fast response time with high fill factor comparing to the reflective LC-SLM. In addition, Compound Photonics introduced their latest 0.55" 4K2K LCoS panels (fill factor ~93%) with ~ 3 micron pixel pitch panel in 2018 [13]. The urgent need of high ppi (~7000 ppi) 4K2K LCoS-SLM is clear in recent years. The high ppi 4K2K IC backplane, nevertheless, usually has the limitation of low driving voltage (< 3.3 V) [14-18]. In this work, 0.7-inch 4K2K IC backplane (pixels ptich ~ 3.74 um with fill factor ~90%) with a 2.4 ms fast response time for the full-phase modulation can be obtained under digital driving scheme with $\Delta V = 1.75$ V. The phase linearity, phase precision, and phase accuracy of our latest LCoS panel were evaluated. Finally, a 3D depth-focus holographic imaging was demonstrated for the potential application of the next generation HUDs.

## 2. EXPERIMENT

A 0.7 in with 4160×2464 pixels, with a pixel pitch of ~3.74 μm (~6907 PPI, FF~90 % from Jasper display Corp) was applied in this study. The LCOS panels were assembled in our fabrication lab. The cell gap was determined from 15 locations of the entire active area. The LCM–1107 is kindly provided by Professor Wu's group. The birefringence values ($\Delta n$) were 0.37 and 0.36; and the $\gamma/K_{11}$ values were 9.0 and 7.4 ms/μm$^2$ at 35 °C and 45 °C at 633 nm, respectively.

## 3. RESULTS

A 0.7-inch 4K2K IC backplane is driven by digital sequence bitplane which defined by $V_{white}$ ($V_w$), $V_{black}$ ($V_b$). The average phase accuracy error % (APA error %) of the commercial JDC *4KSRK* LCoS-SLM is 1.81 % with its default setting. The driving program was optimized for our new *PCU-3-02-HPPI* LCoS-SLM to achieve 0.83 % average phase accuracy error. Both JDC *4KSRK* and *PCU-3-02-HPPI* LCoS-SLMs were driven at controlled operating temperature at 45 °C. The panel response time was measured when gray scale changing from 0 to 255 and 255 to 0 for a maximum phase shift ($\delta_{max}$) transition. The rise and decay time of JDC *4KSRK* panel were 6.0 and 9.9 ms under JDC default driving condition. The rise and decay time of *PCU-3-02-HPPI* were 0.9 and 1.5 ms under driving at $\Delta V = 1.75$ V ($V_w$ = 3.20 V, $V_b$ = 1.45 V). A 2.4 ms fast response time for the full-phase modulation can be obtained from our new LCoS-SLM panel.

Spatially varying phase response as phase precision modulation after linear LUT driving calibration was evaluated on both LCOS panels. The average standard deviation (mSTD) of the phase response from 15 different sectors measured from the entire panel is 0.02 π and 0.10 π-radians of *4KSRK* and our *PCU-3-02-HPPI*, respectively. Our results suggest that the fringing field effect can be suppressed at the smaller cell gap. The pixel-level phase-accuracy error under maximum spatially frequency (max SF=133.5 lp/mm) is 30.46 % and 10.36 % of *4KSRK* and *PCU-3-02-HPPI*, respectively.

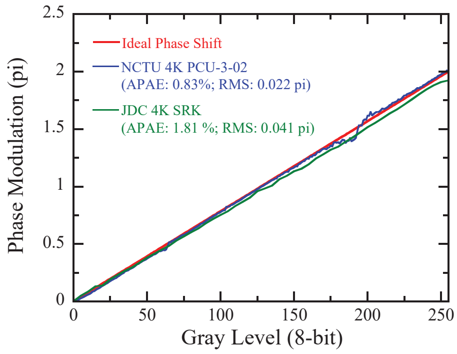


Fig. 1. Measured linear phase shift curve of PCU-3-02 and JDC 4KSRK LCoS SLM at λ = 633 nm.

The d/p values of *4KSRK* and *PCU-3-02-HPPI* are 1.02 and 0.47. The noticeable crosstalk effect decreased maximum phase shift from ~2.0 π to ~0.6 π radians for *4KSRK* due to its d/p value is greater than 1. This is the major reason why the poor imaging quality and low diffraction efficiency compared with 2K1K LCOS panel (*JDC*). The *PCU-3-02-HPPI* with lower d/p ratios could improve the phase accuracy by ~2 times than *4KSRK*. The only limitation for the 4K panel is the small driving voltage (< 3.3 V) which restricted the depth of phase modulation.

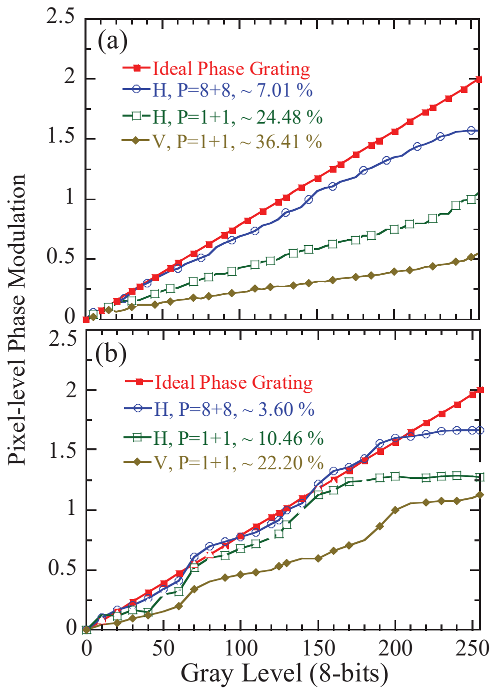


Fig. 2. The pixel-level phase modulation with various spatial frequencies from 1+1, and 8+8 and their grating directions (H and V grating) in 6907 PPI for (a) JDC *4KSRK* with d/p~1.02 and (b) NCTU *PCU-3-02-HPPI* with d/p=0.47.

The phase fluctuation of both panels was further evaluated. The mSTD and average P–P of *4KSRK* were 0.07 π and 6.7 % when the digital voltage inputs of $V_w$ = 3.38 V and $V_b$ = 0.98 V at 45 °C, as shown in Fig. 3 (a). To gain the lower phase fluctuation, the P–P values of *PCU-3-02-HPPI* were 0.11 π and 11.1 % when operated at the $V_w$ = 2.2 V and $V_b$ = 1.0 V with controlled the operation temperature of 35 °C, as shown in Fig. 3 (b). The rise and decay times were found 1.86 ms and 5.36 ms at this driving condition. As shown in Fig. 3, the average P–P of the optimized *PCU-3-02-HPPI* driving scheme is ~4% higher than *4KSRK*. There are two possible reasons for the observed results: (1) The LC rising time of *PCU-3-02-HPPI* (1.86 ms) is much faster than the total clock (*Tclks*) time (3.40 ms) so that the fast LC switching cause the static phase flicker enlargement. (2) The phase fluctuation is disturbed when the memory writing time (0.144 μs) is longer than the imager refreshing time (0.097 μs), which enlarges the noise from the 4K2K LCOS driver.

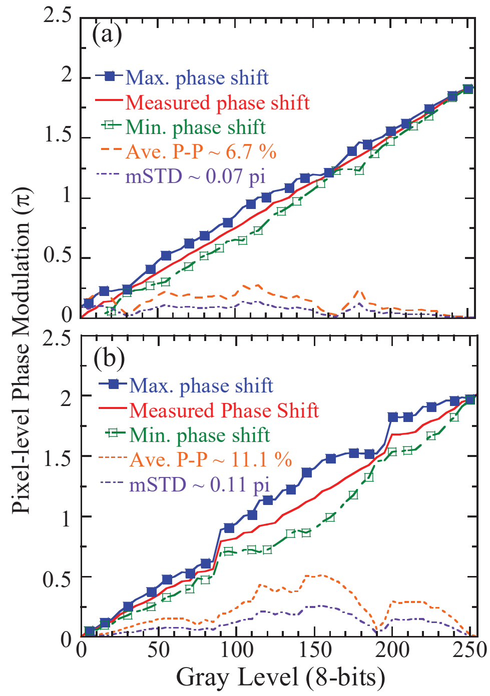


Fig. 3. The temporal fluctuation of phase modulation of (a) JDC *4KSRK* with Tclks=4.16 ms and (b) *PCU-3-02-HPPI* with Tclks=3.40 ms.

The 3D holographic image projection was performed in the calibrated *PCU-3-02-HPPI* LCoS-SLM. A depth focus holographic image was computed for 3D holographic display. The pictures with 3D information in different viewing depth for head up displays (HUD) window were reconstructed from incoming light. Each individual picture was transformed into a phase pattern hologram. The reconstruction holographic results were shown in the Fig. 4.


(a) L = 300 mm (b) L = 400 mm (c) L = 500 mm

Fig.4. Reconstructed images of the HUDs at distances of arrow indicator: (a) L = 300, (b) L = 400, and (c) L = 500 mm, respectively.

## 4. CONCLUSION

The ultrahigh birefringence LC mixtures used in LCOS panel not only minimized the cell gap to speed up the LC response time and suppress the fringing field effects, but also reduced the minimum $\Delta V_{2\pi}$ for phase flicker optimization. Our results suggested that the *Tclks* value, the overall electrical addressing frequency, corresponds to the optical fluctuation frequency. It can be the upper limit for the development of faster LC responses when the application requires a compromise between the switching speed and phase flicker.

We demonstrated the fast response time (0.9 ms and 1.5 ms) of 7000 PPI 4K2K, 0.7-inch *PCU-3-02-HPPI* LCoS-SLM with the acceptable phase fluctuation. It has the advantages to reduce image latency, enlarge FoV, and suppress image speckle effect. It also provides the solution of full-color holographic imaging applications, such as in the near-eye AR glasses, next generation automotive HUDs and holotable/box. Our *PCU–3–02–HPPI* is able to maintain increased linearity and phase precision. The spatial crosstalk effects and temporal fluctuations are still the major challenges owing to the limitation of the driving voltage, the digital addressing frequency, and the noise signal of 4K2K driver.

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